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EXTENDING CUSTOMER ORDER PENETRATION CONCEPTS TO ENGINEERING DESIGNS

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ABSTRACT

Purpose - The customer order decoupling point (CODP) concept addresses the issue of customer engagement in the manufacturing process. This has traditionally been applied to material flows, but has more recently been applied to engineering activities. This later subject becomes of particular importance to companies operating in 'engineer-to-order' (ETO) supply chains, where each order is potentially unique. Existing conceptualisations of ETO are too generic for practical purposes, so there is a need to better understand order penetration in the context of engineering activities, especially design. Hence, we address the question 'how do customer penetration concepts apply to engineering design activities?'

Methodology - A collaborative form of inquiry is adopted, whereby academics and practitioners co-operated to develop a conceptual framework. Within this overarching research design, a focus group of senior practitioners and multiple case studies principally from complex civil and structural engineering as well as scientific equipment projects are used to explore the framework.

Findings - The framework results in a classification of nine potential engineering subclasses, and insight is given into order penetration points, major uncertainties and enablers via the case studies. Focus group findings indicate that different managerial approaches are needed across subclasses.

Implications –The findings give insight for companies that engage directly with customers on a one-to-one basis, outlining the extent of customer penetration in engineering activities, associated operational strategies and choices regarding the co-creation of products with customers. Care should be taken in generalising beyond the sectors addressed in the study.

Originality - The paper refines the definition of the ETO concept, and gives a more complete understanding of customer penetration concepts. It provides a comprehensive reconceptualization of the ETO category, supported by exploratory empirical research.

Keywords: decoupling point, order entry point, postponement, co-creation, engineer-to-order, supply chain.

1. INTRODUCTION

The importance of product customisation has been popularised by a wide range of published work (Lampel and Mintzberg, 1996; Pagh and Cooper, 1998). Customer driven manufacturing has been positioned as a key concept for the factory of the future, and many companies have responded by seeking to develop customer driven manufacturing systems (Rudberg and Olhager, 2003; Wortmann et

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al., 1997). This can be done in a variety of different methods and degrees. A useful way to consider the gradations of customisation possible, developed to facilitate control over the flow of goods, is offered by the Customer Order Decoupling Point (CODP). The CODP describes the way in which customer orders penetrate the 'basic structure' of operations, indicating how deeply a customer order enters into the goods flow (Hoekstra and Romme, 1992). It has since been conceived of as a strategic stocking point that provides a buffer between fluctuating customer orders and smooth production output (Naylor et al., 1999). Upstream of the CODP, activities are typically speculative, aggregated and standardised; downstream of the CODP, activities are typically predictable, attached to known orders, individualized and customised (Lampel and Mintzberg, 1996; Olhager, 2003; Rudberg and Wikner, 2004).

Using the CODP concept, a range of structures can be defined to give a simplified classification of supply chain types. These range from very repetitive 'make-to-stock' supply chains to a very customized 'engineer-to-order' (ETO) structure (Gosling et al., 2007; Hoekstra and Romme, 1992; Olhager, 2003). In the latter type, each item is, to a degree, unique, and the client will often engage with the design process (Gosling and Naim, 2009). Consequently, a much closer integration, and more sophisticated understanding, of the interface between engineering and the whole supply chain is needed (Dekkers et al., 2013; Hicks et al., 2000). To give a more refined way of understanding this interface, a small selection of papers have developed classification systems for design and engineering activities based on CODP related concepts (Dekkers, 2006; Giesberts and Tang, 1992; Gosling et al., 2011; Wikner and Rudberg, 2005a; Winch, 2003). This paper develops understanding in this area, giving a much richer definition of the CODP concept as applied to engineering activities and the degree of novel engineering required of a particular project.

This paper takes the ideas developed by Wikner and Rudberg (2005a), as well as Gosling and Naim (2009), as its starting point. Wikner and Rudberg (2005a) refine the original material flow focus of the decoupling point to include a spectrum of engineering activities ranging from engineer-to-order and engineer-to-stock. This helps to capture complexity in a more complete way in terms of possible configurations, and offers a framework for positioning the CODP in terms of both engineering and production simultaneously. However, after the authors of this current paper presented key ideas from previous research to the advisory board of a large engineering organisation, feedback from senior directors suggested that, firstly, customer penetration concepts were very useful in terms of better understanding the flow of engineering activities but needed finer precision, and secondly, that firms operating in the ETO marketplace sometimes have to conduct collaborative research and also engage with technical design codes to fulfil customer orders. Both of these foundation studies, and many others in the CODP body of knowledge, are conceptual, calling for more empirical exploration. To address these issues, a co-operative inquiry research project was initiated (Heron, 1996), which forms the basis of this paper. The principal arena for the empirical work is complex civil and structural engineering projects and scientific equipment, since these sectors are uniquely positioned to give insight into ETO situations, but we also include input from practitioners with a wide range of experience in different sectors through a focus group.

Since the focus is the application of an operations management concept to engineering activities, it is important to address at the outset what is meant by such activities. Dixon (1966) positioned engineering design work at the intersection of two separate streams. The first stream is primarily scientific-technical, and moves from physical and mathematical science, to engineering design, to engineering technology onto a point where designs are related to the 'conditions of production'. The second stream is cultural-aesthetic, taking in flows from political and sociological movements, as well as industrial and artistic designs. The two streams meet at 'engineering design'. This paper is primarily concerned with the scientific-technical stream, focusing on engineering design. While this paper is primarily based on CODP concepts from the operations management discipline for its theoretical background, it is also informed by engineering management theory and philosophy (Addis, 1990; Bulleit et al., 2014)

The terminology relating to the CODP can be confusing, since alternative definitions and labels have been used, including order penetration points (Olhager, 2003), and order entry points (Dekkers, 2006). Collectively we use the term customer penetration concepts and address the question 'how do customer penetration concepts apply to engineering design activities?' In doing so, we give insight into the trade-offs and challenges in customer driven engineering. The specific research objectives of the paper are to:

- Develop a framework to rationalise customer penetration concepts to engineering design activities.
- Explore the framework via exploratory empirical research methods.

2. LITERATURE REVIEW

2.1 Early Customer Penetration Definitions and Frameworks

An early article by Wemerlov (1984) characterized manufacturing strategy as either make-to-stock (MTS), make-to-order (MTO), or assemble-to-order (ATO), signifying the degree of interaction with the market. MTO strategies have the highest degree of contact. At around the same time, Sharman (1984) argued for the importance of the order penetration point in logistics configuration, which denotes the point at which a product becomes earmarked for a particular customer. In most cases, this point is where product specifications get frozen and the last point at which inventory is held. These early articles set the foundations for the seminal work of Hoekstra and Romme (1992), who, through consultancy work and interaction with academics, developed an expanded and more refined discussion. They positioned the CODP as a planning and control concept, describing the way in which orders penetrate the physical flow.

Hoekstra and Romme (1992) defined five different logistics structures, including buy-to-order, make-to-order, assemble-to-order, make-to-stock, as well as make and ship-to-stock. The risks linked to investments, lead times and estimated costs, Hoekstra and Romme argued, will be different across the structures. Typically, with careful balancing, the CODP will tend to move towards the customer as companies improve. They further argue that the level of aggregation would depend on the specific application, but most of their discussion seems aimed at product group or value stream level. Hence, it is quite possible that companies could manage product groups or value streams across the range of structures at any one time. It is noteworthy for this paper that the ETO situation did not feature as part of Hoekstra and Romme's (1992) classification, but was made explicit in Giesberts and Tang (1992) and Konijnendjik (1993).

A different but highly relevant stream of literature relating to the customisation and standardisation of different work activities began to develop alongside the CODP literature. Lampel and Mintzberg's (1996) seminal paper on the nature of customization provided a foundation for many papers in this area. Based on the logic of aggregation and the logic of individualization, they develop a continuum of strategies to explain how standardization and customization may interact for different elements of a manufacturing process. Although the language and intellectual material used to develop the continuum is quite different, there is much crossover between the structures defined in Hoekstra and Romme (1992) and Giesberts and Tang (1992). Later the two literature streams became more integrated to consider mass customisation, as shown in Rudberg and Wikner (2004).

Figure 1 presents a way of combining the customisation issues raised by Lampel and Mintzberg (1996), and the decoupling point proposed by Hoekstra and Romme (1992). This link was initially made in the postponement literature (Van Hoek, 1998; Yang et al., 2004). The step-wise bar shows the extent of penetration by customers into operational activities, giving six simplified structures. The shaded activities are all performed 'to order' and under certainty of customer requirements. The non-shaded activities are standardised and speculative. The CODP in this case is likely to be strategic stock, where the form of stock varies depending on the position. In the case of the ETO structure it is less clear exactly what is held in stock, an area in which this study gives further insight.

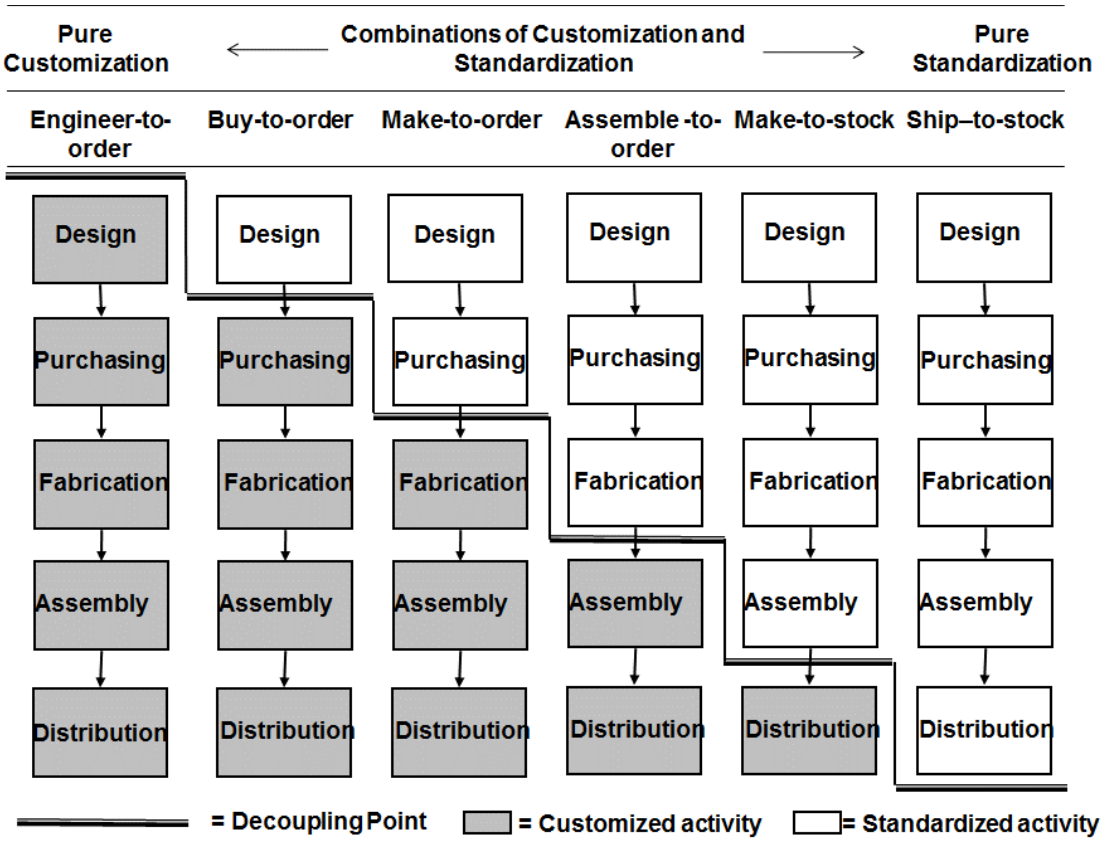

Figure 1: The family of supply chain structures (Adapted from Gosling et al., 2007; Lampel and Mintzberg, 1996; Yang et al., 2004)

Figure 1: The family of supply chain structures (Adapted from (Gosling et al., 2007; Lampel and Mintzberg, 1996; Yang et al., 2004))

2.2 Refining and Extending Basic Concepts

The CODP was further refined by (Wikner and Rudberg, 2005b). The CODP is defined in their study as the point at which decisions are made under uncertainty concerning customer demand. Certainty may pertain to 'what?' 'when?' and 'how much?'. Using an illustrative case, they show how these aspects of uncertainty change by degrees over time, rather than an abrupt switch from complete uncertainty to certainty. To offer a more accurate representation, they develop the customer order decoupling zone to take account of changing levels of certainty over time. Research has also addressed the strategic context of the CODP (Olhager, 2010; Rudberg and Olhager, 2003). The influences on the optimal positioning of the decoupling point can be complex when positioned within the strategic context. Olhager (2003), expanding the early work of Hoekstra and Romme (1992), suggested market, product and production related factors all interact to give an optimal decoupling positioning. The paper contributes by expanding our understanding of the complexity and influences on the difficult issue of 'shifting' between structures.

The postponement literature also links with and develops our understanding of the CODP. Indeed, many studies of postponement make explicit reference to the CODP (Skipworth and Harrison, 2004; Wong et al., 2011; Wong et al., 2009). A useful distinction is made in this literature between 'postpone', whereby certain activities are delayed until orders are received, and 'anticipate', whereby activities are performed speculatively (Zinn and Bowersox, 1988). This stream of literature develops our understanding of what can be postponed, for instance in distribution (Zinn and Bowersox, 1988), product form (Skipworth and Harrison, 2004), or across the supply chain in general (Pagh and Cooper, 1998).

2.3 Relevant Empirical Studies

While many of the aforementioned studies are conceptual, a few noteworthy industry and case applications are evident. Wortmann et al. (1997) present a comprehensive discussion of customer driven manufacturing, illustrating the range of structures with in-depth case studies. They describe case studies in capital goods, medical equipment, paper manufacturing and shipbuilding sectors. Amaro et al. (1999) analyse a range of case studies in manufacturing sectors, focusing on non-make-to-stock structures. Other noteworthy empirical contributions include illustrative cases from the food processing industry (Van Donk, 2001), motors (Skipworth and Harrison, 2004), construction (Gosling et al., 2013), coffee (Wong et al., 2011) and manufacturing engineering companies (Dekkers, 2006).

2.4 Engineering Management

The scoping of this paper is aimed at the ETO supply chain, where all production dimensions are customised for each order and there is some degree of engineering work (Gosling and Naim, 2009; Little et al., 2000). While this focus gives a clear boundary, the degree of engineering work involved within this production situation lacks clarity. A range of studies that explicitly discuss engineering activities within the customer penetration point context is shown in Table 1. This helps to give a sense of the spectrum of potential situations, and builds a foundation for later elements of the paper.

Within the construction management literature Winch (2003) distinguishes between production information flow and material flow, suggesting that production information flow can be divided up into concept to order, design to order and make to order strategies, thereby offering potential ETO subclasses. A different approach was proposed by Giesberts and Tang (1992), who indicated a potential separation of production and engineering order points, rather than a linear approach. Wikner and Rudberg (2005a) expand this line of argument, giving detailed models for the decoupling of engineering and production related activities of the supply chain. An engineering dimension and production dimension are advocated with the engineering dimension ranging from ETO, where a new product is designed, and engineer to stock (ETS), where a design is already 'in stock'. Between ETO and ETS engineering modifications to existing product designs are used in varying degrees.

(Wikner and Rudberg, 2005a)	**(Giesberts and Tang, 1992)**	**(Dekkers, 2006)**	**(Amaro et al., 1999)**	**(Winch, 2003)**
Engineer-to-stock	Standard	Transfer production instructions	Take existing design	Make to order
		Transform standard information	Pick from set of options	Design to order
		Adaptation of existing configurations	Modify existing design	
Engineer-to-order	Customer Specific	Total dedicated design	Produce new design	Concept to order

Table 1: Categorizations of design and engineering activities in the CODP literature

Dekkers (2006), perhaps giving the most comprehensive account of the CODP as applied to engineering activities, distinguishes between the customer order entry point and the order specification entry point. The former relates to the point where an order enters the material flow, whereas the latter relates to the order entry point within engineering work. Four different order specification entry points are identified, ranging from a total dedicated design to standard designs. Both Wikner and Rudberg (2005a) and Dekkers (2006) explore the way in which production and engineering points interact. In a more recent comprehensive review, Dekkers et al. (2013) re-emphasize the lack of research to enable further understanding of these interactions since these papers were published. Further potential design and engineering categories are given in Amaro et al. (1999). Gosling et al. (2011) consider engineering dimensions in the context of the potential for research and development activities may be performed to order as part of engineering work.

There is ambiguity as to the exact nature of what is held 'in stock' in an engineering decoupling point. These are often regarded as drawings or information (Dekkers, 2006; Gosling and Naim, 2009; Wikner and Rudberg, 2005a). The latter category has not been well established within the context of the CODP approach. Mason-Jones and Towill (1999) explicitly define and formalise the information decoupling point, applying decoupling point logic to the order information flow pipeline. They define is as the point in the information pipeline to which marketplace orders penetrates without modification, where marketplace and forecast driven information flows meet (Mason-Jones and Towill, 1999). In their view, information becomes distorted upstream of the decoupling point. A number of information enrichment strategies are proposed, but the authors do not give much detail as to what information may be held 'in stock' for engineering or design purposes.

2.5 Recent Developments

A comprehensive paper by Wikner (2014) re-iterates the importance of customer order based management and develops decision categories within a decoupling theory. In doing so, the paper offers a more philosophical reflection on order penetration concepts. Wikner (2014) concludes that there are opportunities and gaps for further research in establishing the preconditions for flow, and the link between decoupling point and customer interactions. Akinc and Meredith (2015) revisit the traditional trade-offs between product customization and lead time within the context of different CODP environments, focusing on the managerial challenges, both strategic and day to day, arising in make-to-forecast situations. In the area of ETO production situations, several recent publications have moved forward the debate. Mello et al. (2015) and Gosling et al. (2015) highlight the complexities arising from interdependencies between engineering and production, with the former suggesting that co-ordination mechanisms are needed to integrate engineering and production. Willner et al. (2016), acknowledging the need for more clarity in the ETO sector, seek to build archetypes for ETO firms. Based on volume and engineering complexity, rather than using order penetration concepts as a foundation, they suggest complex, basic, repeatable and non-competitive ETO archetypes. Both the latter papers find that ETO environments are challenging, under researched, and in need of more clarity.

3. RESEARCH METHODOLOGY

3.1 Research Strategy

In the process of developing a framework for order penetration points in engineering activities, the study developed through iterations which were informed by literature, a focus group, and case study activities. Figure 2 visualises the overall structure of the research design. It shows the iterations between theory and practice in developing the framework. Early interactions related closely with customization and decoupling point frameworks (Hoekstra and Romme, 1992; Lampel and Mintzberg, 1996), as well as the ETO body of knowledge (Gosling and Naim, 2009). The next iteration related to applying decoupling point concepts to the engineering dimension (Dekkers, 2006; Wikner and Rudberg, 2005a). The final iteration related to the philosophy of engineering, in particular the use and establishment of codes and standards (Addis, 1990; Bulleit et al., 2014). These streams of knowledge were used to interact with practitioners through a 'co-operative inquiry', which is explained more fully later. A further point to note is that prior to the generation of a draft framework, the approach was based on a more informal and less structured approach, allowing ideas to develop 'organically'. Once a draft was developed, methods became more structured and formalised. A focus group and multiple case studies were used in the later stages. These are explained and justified in greater depth below.

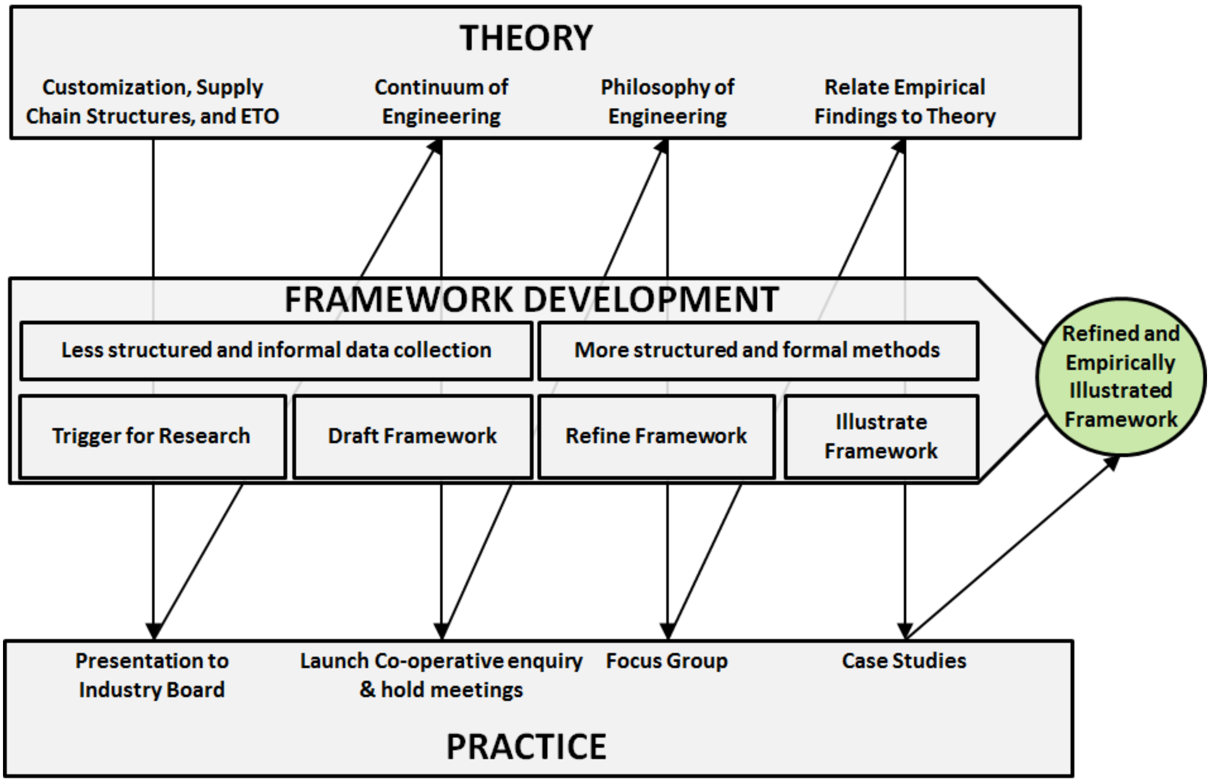

Figure 2: Overview of research design

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Research activities were underpinned by 'co-operative inquiry', whereby a practitioner was involved in planning, directing, reflecting on, and in the presentation of the research (Heron, 1996). Such participation can facilitate experiential, presentational, propositional and practical progress and transformation (Heron, 1996). It is also consistent with Ottoson and Bjork (2004), who argue that when dealing with complex adaptive systems, such as engineering and product development projects, researchers should consider 'insider' and 'participatory' approaches to research. The co-operative inquiry research was initiated through a presentation given to an advisory group for a large engineering organisation and its supply chain. Following this, an 'inquiry group' was formed (Heron, 1996), consisting of the paper's authors as the core members, but with the wider advisory group feeding in as appropriate. This led to an iterative process of conceptual development, cycling between the experience of industry professionals and researchers, with reflection on relevant literature and practice. Members of the advisory board contributed, participated and were consulted at various stages of the inquiry. Since the research seeks to build theory, and is exploratory, a focus group was chosen in order to gather feedback on the dimensions of different engineering subclasses and order penetration concepts. Multiple case studies were then used to illustrate the different dimensions of the framework.

In relation to figure 2, the 'unpacking' of the ETO supply chain occurred during the 'Trigger for Research' and 'Draft Framework' phases, based on co-operative enquiry discussions and iterations with the literature. A range of dimensions were developed and refined through presentations, reading and discussions. The definitions, number of categories and the labels were refined during these iterations, allowing for a well-developed version of the framework to be presented during the focus group. The latter then allowed richer descriptions and the mapping of examples onto the framework to be undertaken. It also afforded an opportunity for discussion of potential implications and critique.

3.2 Focus Group and Case Study Research Methods

Focus groups can be beneficial for identification of major themes and are useful for exploratory investigation of particular issues (Krueger and Casey, 2009; Rodrigues et al., 2010). It is also useful to support construct development and establish major themes for further case study research (Rodrigues et al., 2010). The optimum number of participants is between 6-10 (Krueger and Casey, 2009), and the group composition should be designed to keep a balance of similarities and differences between participants. In addition to three academics with expertise in engineering, lean manufacturing, supply chain management and procurement, as well as a research project manager experienced in managing research and development projects, the non-academic contributors, which represented senior figures in the UK industry, are summarised in Table 2, making the overall number of participants for the focus group ten. While table 2 reports the current position of the attendees, they had a wide range of experience in major engineering projects, covering defence and nuclear sectors, tunnelling, to major building projects, as well as road, rail and power infrastructure schemes. Draft versions of the framework, as well as key ideas from the literature, were presented and a discussion between participants was facilitated by the corresponding author. The focus group was recorded, transcribed and themed.

Position	Sector / Specialism	Type of Organisation	Approximate Employees / Turnover	Major area of Experience
Technical Director	Complex Civil Engineering	Main Contractor	3900 / £1.1billion	Engineering Management
Commercial Director	Complex Civil Engineering	Main Contractor	3900 / £1.1billion	Customer Engagement
Managing Director	Procurement Consultancy	Consultancy	3 / N/A	Procuring Complex Projects
New Product Development Manager	Engineering Contracting	Engineering Professional Body	280 / £15 million	Engineering Support
Supply Chain Manager	Fit out, Construction and Engineering	Main Contractor	2460 / £1.5 billion	Engineering Management
Bids Manager	Complex Civil Engineering	Main Contractor	25000 / £6.6 billion	Customer Engagement
Partner	Legal Advisory in Engineering	Law Firm	2350 / £325 million	Engineering Support

Table 2: Overview of Focus Group Participants

The case studies are intended to be exploratory, helping to develop theory and illustrate the categories developed during the conceptual development and focus group phases. Cases should be purposefully selected to best illuminate the phenomena under scrutiny (Yin, 2003). In this study, the characteristics of the ETO situation were purposefully sought: products and projects with a degree of engineering in customer order fulfilment. Further to this, cases were targeted to cover the range of subclasses identified during the conceptual development phase. This purposeful selection criteria was then balanced with pragmatic concerns regarding willingness to participate and availability of cases.

Case studies should be selected with a sense of purpose (Stake, 1994). This study sought cases that offer ‘useful variation on dimensions of theoretical interest’ (Seawright and Gerring, 2008). Hence, efforts were made to include coverage of the framework developed. Organizations and projects were targeted with the belief that they would further refine the understanding of ETO and customer penetration concepts. The present paper focuses on engineering and construction industry categories to give further insight into ETO subclasses. Such industries typically have high levels of customer interaction in engineering (Gosling and Naim, 2009), displaying a tendency towards ETO operations. Further, the professionalization of codes and standards is mature in this sector. While this does not cover all potential industries, it does offer the potential to cover the subcategories proposed in the framework. Case study organizations with a known interest in ETO, and practicalities such as the willingness of interviewees to participate pro-actively in a research programme, was also considered. Projects were selected with the intention of covering the range of theoretical dimensions in the classification, including research, codes and standards and existing designs. As part of the case study protocol, which is outlined in appendix 1, interviewees were asked to discuss projects they have been involved with as linked to the subclasses

Table 3 shows the range of projects included, as well as approximate value and timescale to give a sense of scale. They cover wind energy, construction, civil engineering, manufacturing companies and large scale complex optics sectors. A range of people were interviewed as part of this process: research and development manager and chief scientist for site visit (Project 1), Sales Director (Project 2), Project Manager for site visit and Director for further discussion (Project 3), Programme Manager and Client (Project 4), Operations and Supply Chain Director (Project 5), Commercial Manager and Lead Engineer for site visit (Project 6), Lead architect and specialist pre-fabrication architect (Project 7), Sales Director (Project 8). Guided site tours were included in projects 1, 3, 6 and 8. This was requested in all cases, but only possible in those listed. Interviews and tours were followed up with email validation of notes and key ideas discussed, and supporting web site and case study related documents were occasionally used to give further detail for the technical aspects of individual cases. A limitation of this approach is that for some of the case studies only single respondents were conducted. Single interviews can be appropriate when richness of data is key, and can be obtained by a single informant (Voss et al., 2002). This issue must also be considered within the broader context of the research design, and the exploratory nature of the cases.

Interviews followed a semi-structured protocol, as shown in appendix 1. This included a general introduction to company and markets, as well as probing a selection of projects to get a sense of which projects within a company portfolio would be best to focus on. In some cases a project was discussed and agreed in advance of the meeting. The interviewee was then shown the conceptual framework developed in the first phase, and asked to relate a project to the framework. This often led to a detailed discussion of the amount of novel engineering work undertaken, the amount and type of work undertaken speculatively, and the type of activities performed 'to-order'. Corresponding questions were asked concerning the nature of stock held and the type of information held as assets. Once a project was categorised according to a particular subclass, they were asked to describe problems and challenges encountered, and enablers for such projects.

Project	Sector	Detail	Total Project Value (Approx)	Total Project Time (Approx)
1	Telescopic Lenses	Prototype telescope mirror segments	£5m	Ongoing (estimated 5-10 years)
2	Infrastructure – Road	200m span bowstring arch bridge	£55m	2.5 years
3	Infrastructure – Rail	Redevelopment and enlargement of major London Station	£250m	Ongoing (estimated 4 years)
4	Infrastructure – Road	Smart motorways scheme	£200m	Ongoing (estimated 3 years)
5	Commercial Building	127m high iconic office development	£130m	5 years
6	Infrastructure – Road	Bypass scheme access bridge	£90m	2 years
7	Residential Building	Modular Student Accommodation	£30.7m	1 year
8	Wind Energy	Wind Turbine Tower Fabrication	£20m	2 years

Table 3: Overview of Primary Case Studies

4. A CLASSIFICATION OF ENGINEER-TO-ORDER SUPPLY CHAINS

Through the initial co-operative inquiry activities, and through interaction with the literature, the first conceptual stage was to 'unpack' the ETO supply chain to explore potential order penetration positions.

The logic for the categorization is shown in Figure 3. It indicates that the design activities of the ETO supply chain can be subdivided into three broad categories: research, code and standards and existing designs. These, in turn, can be further refined to give engineering 'subclasses'. The three broad categories are defined as follows, and will be explained in greater depth below.

- Research - involve research and development activities after a customer order has been received. Research may be commissioned in a wide range of areas, but as stated earlier in the paper, we focus on research that directly relates to engineering design flows.
- Codes and Standards - require either the creation or integration of codes and standards for a particular customer order, as well as those that develop unique designs which take such codes and standards as the starting point.
- Existing Designs - take existing designs, drawings and subsystems as the starting point.

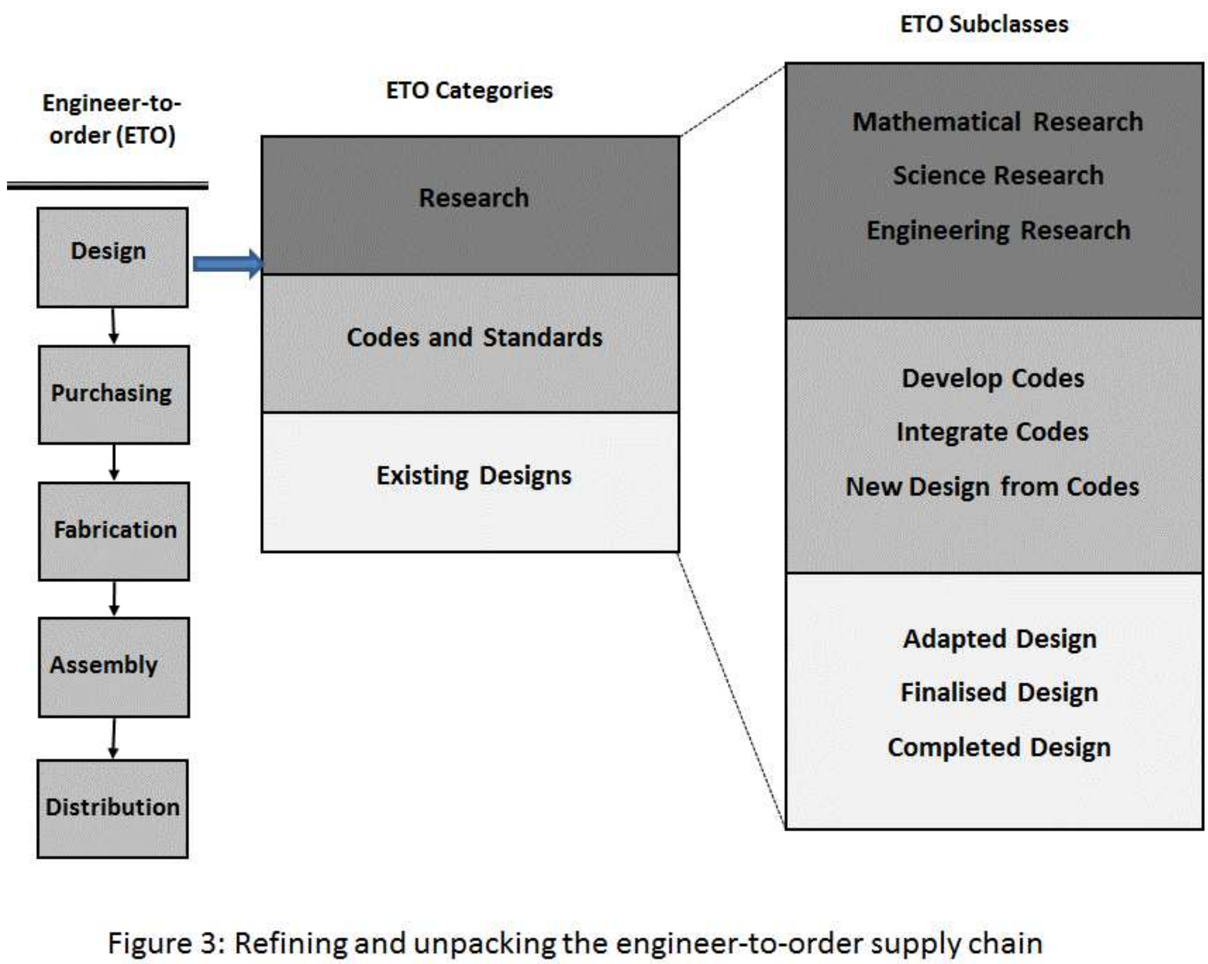

Figure 3: Refining and unpacking the engineer-to-order supply chain

This 'unpacking' of the ETO chain leads to a more detailed conceptual phase, where a framework to rationalise customer penetration concepts for engineering designs was developed, which is shown in Figure 4. This continuum gives nine potential structures for controlling the flow of design and engineering activities. These provide a basis for considering the level of customization and standardization in design activities, as well as considering those activities that are speculative and those that are performed to a specific customer order. As with Figure 1, shaded activities are customised for specific customers, whereas non-shaded activities are standardised and speculative. The customer penetration point is indicated for each subclass.

In the Research subclasses, research and development is performed 'to-order'. This may include proof of concept, testing, or even fundamental research to establish principles for a final solution. The first subclass within this category is Mathematics Research. In this subclass, the theoretical principles are unclear, and it is not even obvious that a solution exists at all. The second type of subclass within this category is Science Research. In this subclass, the theoretical foundations are likely to exist in principle, but the application is uncertain. A further subclass within this category is Engineering Research. In this subclass, testing of materials, principles or applications is required. Petroski (1996) offers a useful distinction between science and engineering: "*design and development most distinguishes engineering from science, which is principally concerned with understanding the world as it is*" (Petroski, 1996 p2). Hence, in Engineering Research, the primary driver is knowledge intended for the purpose of design engineering, rather than as is the case in science and mathematics, where the purpose is to increase our understanding of the nature of things in a more general sense (Bulleit, 2012).

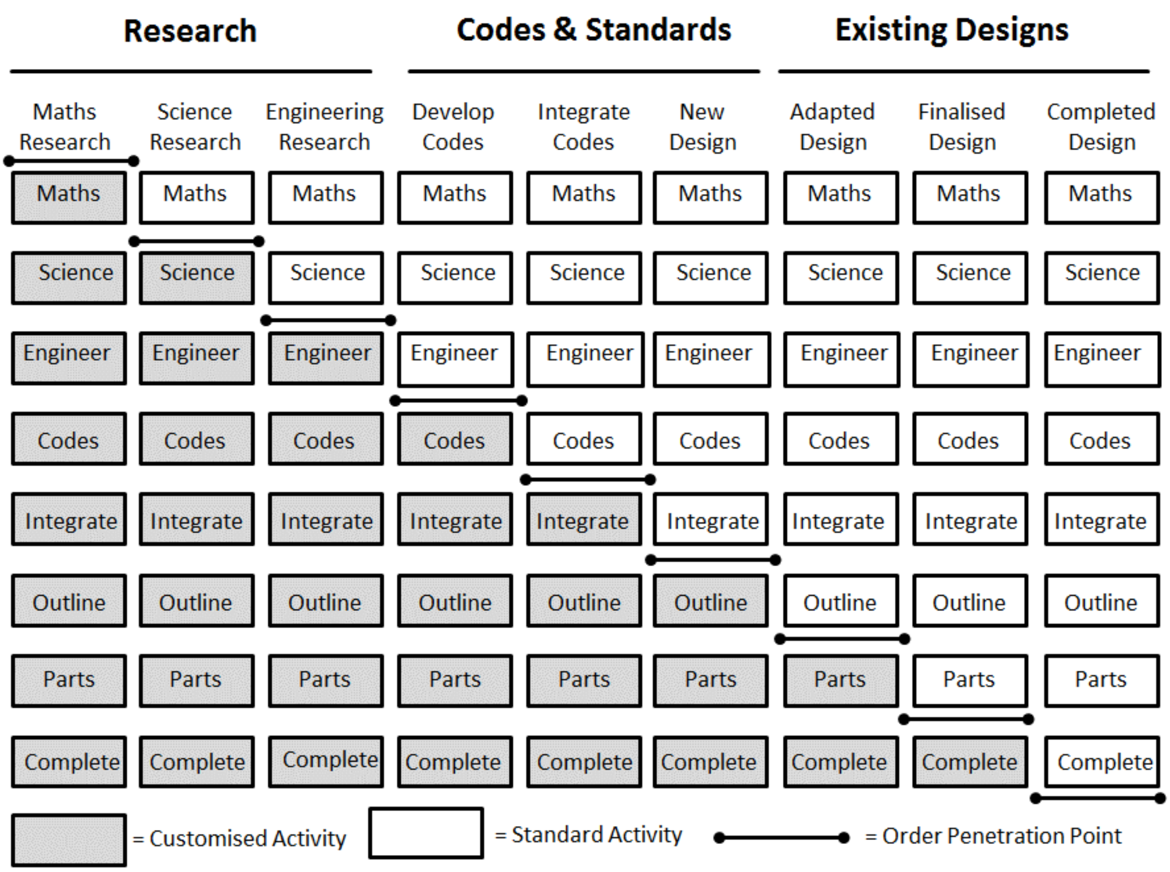

Figure 4: Continuum of Engineering Categories and Subclasses

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The next category is Codes and Standards. In order to define minimum standards, and enhance consistency, clarity and safety, as well as constraining the size of the domain from which decisions should be made, communities of technology practitioners often use formal codes of practice to govern the design of artefacts (Shapiro, 1997). Such codes might be prescriptive in nature, for example specifying the type of materials to be used for a structure, or performance based, such as setting out how a structure should perform under different conditions (Foliente, 2000). Professional societies and national standard bodies are the most prolific bodies for the writing and publishing of codes. Engineers must 'decode' these general, universal codes in order to localize artefacts to the specific context and customer requirements. Hence, in this category of subclasses, it is up to the companies involved to demonstrate that the proposed solution meets the codes and standards applicable for the particular project. Examples include British Standards (British Standards Institution, 2004) and Eurocode guidelines (Eurocodes Expert Manager, 2009), Institute for Electrical Engineers Standards Association, ASCE (American Society of Civil Engineers, 2005) or those published by institutes such as the American Concrete Institute.

Develop Codes is the first subclass in this category. Modern codes have typically evolved over many years, influenced by high profile case studies, academia, trade research, government guidelines, innovations from practicing engineers and societal desires (Bulleit, 2012). The majority of developments in codes of practice follow test results from engineering research. New codes would have to be developed in order to articulate any new developments. These may be smaller scale modification to existing codes and standards or may by engineering revolutions (1990). In the second subclass, Integrate Codes, new codes would have to be integrated with existing codes for more general market acceptance. This may be undertaken through a structured 'departures' process or by redrafting of codes by relevant institutions. The third subclass in this category is New Design (from Codes). Such solutions begin from a blank sheet as far as the solution is concerned, but use established codes, standards, and principles to develop designs. This relates to what has been described elsewhere as ‘establishing project design rules’ (Baldwin and Clark, 2000).

In the Existing Designs subclasses, the principal challenge is to bring standard designs together for the needs of a particular project. For example, the form, layout and integration will need to be considered on an order by order basis, but previous designs will be available, either stored in expert systems or as drawings. In the Adapted Design subclass, outline designs are used as the starting point. This will involve taking customer requirements, and using combinations of existing outline designs as the starting point. Existing outline designs and subsystems are integrated within the parameters of the brief. Finalised Design is the next subclass in the classification. This assembles existing components for a particular solution. The design solution is built up from an established set of parts, each with known characteristics and with the rules for overall configuration being set down. The final subclass is Completed Design. Here, designs are completed, yielding standard product designs that are exploited to customer requirements. At this point, the state is similar to the ‘buy-to-order’ structure described in production decoupling point classifications (Hoekstra and Romme, 1992).

5. FOCUS GROUP FINDINGS

Within the CODP literature, there has been discussion of the competitive trade-offs apparent at different decoupling positions. Barlow et al (2003), addressing traditional material flow CODP, argue that trade-offs for competitive priorities exist in relation to different positions for the CODP, showing that levels of customization affect lead time and cost. Findings from the focus group suggest that it is likely that there are different opportunity and risk profiles associated with different subclasses, where the outcomes are more predictable and less complex as we move towards complete designs. As suggested by one participant *“There are different opportunity and risk profiles across the spectrum, as you veer from left to right”* (Commercial Director). Based on these arguments, Figure 5 visualises these trade-offs. It suggests that the more customisation that is offered, the longer lead times tend to be, and the more cost involved in comparison to a standard offering. However, there are potential gains to be made by customer service and co-creation, as well as innovative engineering work. This also has implications for complexity, as outlined by another participant *“They [the subclasses] determine how predictable, how complex, how much understanding we have in particular area*” (Technical Director).

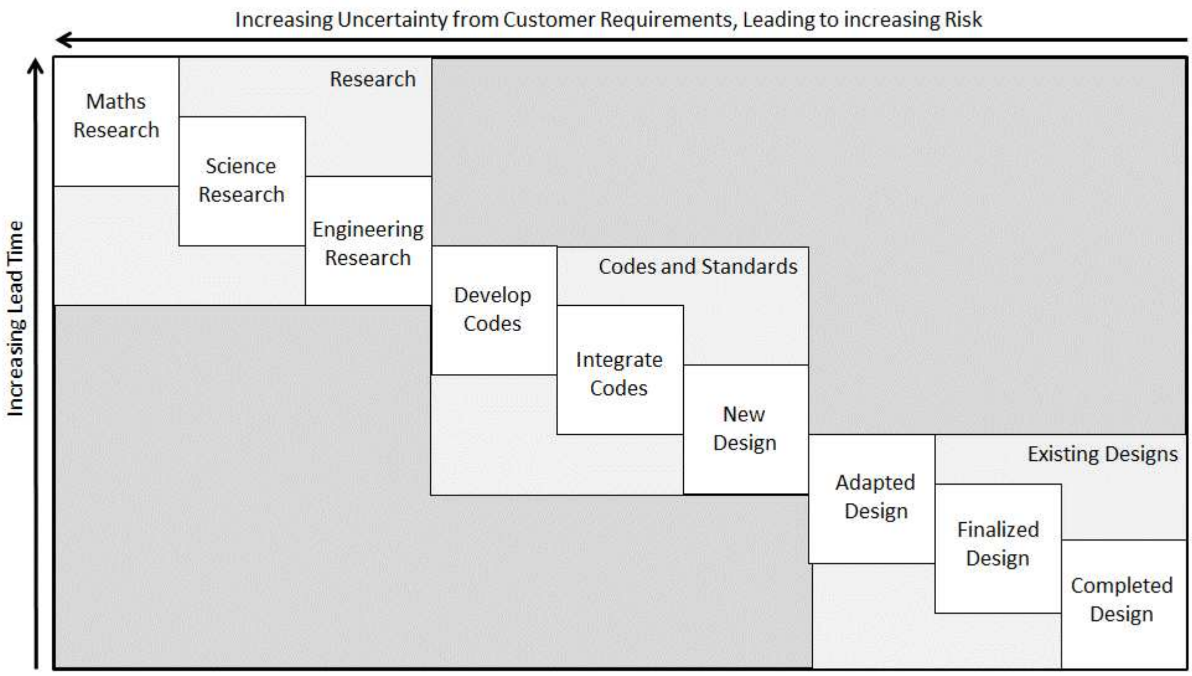

Figure 5: Trade-offs across the Different Subclass Positions

Figure 5: Trade-offs across the Different Subclass Positions

Olhager (2003) highlights the strategic importance of choosing the appropriate order penetration point, and considers the factors that may lead to 'shifting' either forwards to a more standard offering and reduce the number of activities that are based on uncertain information, or backwards to allow more customer interaction. Evidence from the focus group suggests that, from a procurement perspective, companies do not take such considerations into account in terms of engineering activities. *"Do procurement agents fully understand the nature of such subclasses.....as a basis for positioning? Probably not"* (Consultant). In the case of material flow decoupling points, Olhager (2003) argued that market, product and production factors combine to inform the ideal positioning. In the case of customer penetration in engineering design activities, it is likely that abilities and capabilities in relation to knowledge play a large part. As acknowledged in the focus group *"capabilities, as well those in the supply chain, will have a large bearing on the approach adopted"* (Supply Chain Manager), where *"knowledge management is key"* (New Product Development Manager).

A range of publications have espoused the importance of alignment of strategy with structure or situation (Naim and Gosling, 2011; Naylor et al., 1999; Sanderson and Cox, 2008). This areas was of significant interest to the participants *"I'm curious about the idea of alignment.... you will never come up with a one size fits all solution"* (Commercial Director). Furthermore, it was argued, *"the way you incentivize and contract with the supply chain would differ across subclasses"* (Procurement Consultant). Unsuitable contracts, for example, have long been found to allocate risk inadequately among the supply chain (Barnes, 1983). A participant also raised the issue of partnerships within the framework: "*What is the role of formal partnering and alliancing arrangements within the framework?....possibly it plays out differently in the different columns [subclasses]"* (Bids Manager). The use of appropriate collaborative partnerships, tailored to supply chain type, has been recognised in the supply chain literature (Bask, 2001). In the case of a research subclass, for example, it was suggested that collaborative ties with universities, as well as proximity to other new set ups, expertise and support structures may be beneficial.

6. CASE STUDIES OF THE ENGINEERING SUBCLASSES

As noted in the method section, the case phase of the research is intended to be exploratory, comparing and relating the classification to case studies . Figure 6 provides the main features of the case studies, including highlighting the order penetration characteristics, defined by "Starting Point for Design" and "Nature of Customer Input". We also analyse major uncertainties and enablers for each case.

6.1 Research Subclass Cases

Project 1 exemplifies the Science Research subclass. It relates to a project to develop the next generation manufacturing technology for large scale optics. A group of research and development companies were commissioned to undertake a manufacturing feasibility study to provide the mirror component for a large scale telescope. The project, to provide seven segments for a large scale telescope, makes use of a new process, and new developments in nanotechnology, so that the surface of each segment is polished to an extremely well defined profile within close tolerances. It is a very experimental set up, bringing together scientists and bespoke technology. The polishing and smoothing process involved is not yet proven, and was a major uncertainty in the project. Engineering work flows from a foundation of research papers and experiment results. Intellectual Property also forms a foundation and target for some of research and development activities. Interactions with the client revolved around a 'feasibility study' outline and specification, which gave an open brief to respond to. A consortium structure help to bring in expertise in delivering the feasibility study.

Project 2 illustrates the *engineering research* subclass, which refers to a bowstring arch bridge design with a span of almost 200m. It is situated in the UK with a challenging tidal environment and significant ecological constraints. Built in muddy estuary environment, the engineering design had to take into account wind tunnel and structural testing to ensure robustness in terms of withstanding the tidal range and estimated wind speeds. Academic partners were included to facilitate engineering tests. Interactions with the customer typically related to approvals for the proposed engineering designs. Major uncertainties related to the performance under tidal conditions, as well as engineering phases that involved concurrent engineering. The company has a long heritage of bridge engineering, and has built up expertise in the design and management of such projects.

	Research		Codes and Standards			Existing Designs		
	Science Research	**Engineering Research**	**Develop Codes**	**Integrate Codes**	**New Design**	**Adapted Design**	**Finalized Design**	**Complete Design**
Case	1. Telescopic Lenses	2. Bridge	3. Rail	4. Smart Motorway	5. Iconic HQ	6. Bridge	7. Halls of Residence	8. Wind Towers
Company Type	Manufacturing Consortium	Manufacturer	Civil Engineering	Civil Engineering	Construction	Manufacturer	Construction	Manufacturer
Customer Type	Government	Engineering Contractors	Government	Government	Developers	Engineering Contractors	Developers	Energy Companies
Starting Point for Design	Academic Papers and Experiments	Problem Brief & Codes	Updating of Codes & Standards	Departure from Codes & Standards	Codes, Standards, Case Studies	Building System	Module Designs	Approved Designs
Nature of Customer Input	Feasibility Specifications with Open Brief	Constraint Specification & Approvals	Tendering Documentation & Negotiation	Tendering Documentation & Negotiation	Tendering Documentation & Negotiation	Requirements &Technical Approvals	Requirements & Technical Approvals	Order with Project Documentation

Figure 6: Emergent findings from the case studies.

Figure 6: Emergent findings from the case studies.

6.2 Codes and Standards Subclass Cases

Project 3 offers an example of the Develop Codes subclass. This refers to a significant redevelopment of a major London train station, which includes significant engineering and construction work for station buildings, bridges, platforms, as well as power and plant rooms. The building and platforms are subject to heritage regulations. Innovative engineering solutions were required while working with the existing fabric, for example restoring traditional brick arches, which are rarely used in modern construction. Working with existing fabric, and the uncertainty of the London underground called for innovative adaptation of accepted codes, requiring technical teams with experience of adapting codes. The latter involves consulting libraries of codes, and where appropriate, challenging through new solutions. The customer was engaged through a tendering process, and further negotiation of codes and standards was required as the project progressed. Key enablers were a focus on innovation, knowledge management and colocation arrangements onsite.

Project 4 relates to a ‘smart motorway’ scheme in the UK, and exemplifies the Integrate Codes subclass. Motorway schemes with embedded technology have been implemented through various parts of the UK infrastructure grid. New technology is added to the road to increase the safety and reliability of journeys. In the UK, a design manual for road and bridges (Highways Agency, 2015) establishes the standards relating to the design, assessment and operation of such motorways. The Smart Motorways schemes are innovative and, at times, push boundaries in terms of design standards, leading to a wide range of ‘departures from standards’. This is particularly the case when older existing infrastructure has to be raised to current standards. A major uncertainty was integrating and assessing the impact of new technologies. Customer engagement included working groups and consultations with key stakeholders.

The New Design subclass type is best described as ‘iconic’ designs, since the principles, codes and standards are established, but new designs are developed. Project 5, an award winning 28 storey tower with adjacent structure, illustrates this category. Situated in the London financial district, the design is developed as a series of overlapping curved shells with highly reflective façades. It is innovative in terms of creative design, but also surpasses requirements for carbon reduction and solar glare. While basic codes and standards were not challenged, there is significant creative freedom and engineering judgements exercised in the use of these codes. Key enablers are long term relationships with suppliers, as well as design and programme management expertise.

6.3 Existing Design Cases

Project 6 gives an illustration of the Adapted Design subclass. This case profiles an arch system bridge, manufactured off-site, within a bypass scheme in South Wales. The bridge was based on a Bebo arch system standard design. The system articulates construction standards and procedures to follow, which extend to fabrication, handling and transportation, assembly and installation, backfilling and inspection. A major feature of the Bebo system design is the arch element. These are pre-cast from standard moulds. Standards are specified for the casting, lifting, storage and haulage of the arches. The system also incorporates standard interfaces for 'stitching' the arches together. This design incorporated 22 pre-cast arches to span the bypass. The outline design had to address a number of design challenges and adaptations. The use of bevelled tunnel endings, rather than square, which was favoured by the client, as well as challenging slope of the site, meant that established systems had to be cleverly incorporated into the design solution. Expert systems were a key enabler, and were used to facilitate engagement with the customer.

Project 7 illustrates the Finalized Design subclass. This is a scheme to develop student accommodation block in London. The main features of the design were the use of four standardised pre-manufactured room designs, which repeated throughout the scheme. These designs have been developed through successful case studies and lessons learnt process. A specialist manufacturer was engaged to manage this element of the construction. These were then integrated into a standard structural design. Interactions with the customer focused on fitting requirements to existing module designs, where the uncertainties to be managed were challenging logistics and module variations.

The last of the standard design cases, Project 8, relates to the design of wind turbine towers, and demonstrates Completed Design engineering subclass. The manufacturer involved made substantial speculative investment in technology, capacity and the accumulation of 'know how' in order to enter the market. The latter involved inviting worldwide specialist and consultants to analyse the production facilitates and educate workers the company. Hence, process expertise is an enabler. This involvement extended to the construction of a purpose built £38 million factory. Designs are standard, meeting international guidelines and quality accreditation criteria, but are manufactured to order with no speculative stockholding. A major uncertainty for this product is the floor fixing, where towers join the site.

7. DISCUSSION AND CONCLUSION

This paper has investigated the application of customer penetration concepts to design and engineering activities, addressing the question 'how do customer penetration concepts apply to engineering design activities?' A co-operative inquiry approach was utilised, including interaction with a company advisory board, a focus group and multiple case studies. This resulted in a framework of nine engineering subclasses. These are presented as a continuum of strategies, clustered under Research, Codes and Standards, and Existing Designs subclasses. The first category raises the interesting possibility that research might have to be undertaken 'to-order' as part of an ETO project, an area that has received little discussion in the literature. The second category addresses the development and application of codes and standards, and how specific customer orders may challenge or engage with such codes. The final category relates to existing designs, and resonates much more strongly with existing literature in the area of customer penetration and engineering adaptations.

The framework and strategies were firstly conceptualised before initial scrutiny via a focus group and then empirical matching via exploratory case studies. Both of these phases of the research indicate that the original conceptual framework is of relevance to practice and therefore has credibility. Eight case studies were analysed and described. The cases cover wind energy, civil engineering, as well as nanotechnology and optics. These were classified along the spectrum of subclasses developed, and some of the strategic implications of the positioning have been discussed. Through the focus group, the paper offers tentative propositions about trade-offs and strategic areas that may need to be aligned with subclasses, including contract selection, knowledge management, approaches to partnerships and procurement mechanisms. The case descriptions give detail as to the challenges and strategies applied across the range of subclasses. The cases give insight into the nature of 'stock' held in engineering design processes, suggesting expertise, knowledge and professionalism, as well as design and information repositories, are what is required.

The primary contribution of this paper is that it refines our understanding of how customer penetration concepts apply to engineering design activities, providing a new framework for researchers and practitioners to consider the extent of customer engagement. Building on Wikner and Rudberg (2005a) and Gosling and Naim (2009), the former being a purely conceptual study and the latter a literature review, our paper enriches our understanding of what is meant by engineering-to-order, by determining a finer resolution of eight distinct sub-classes, and the operational and supply chain options open to companies as provided . In doing so, it integrates engineering management concepts, such as the use of technical codes and standards of practice, with operations management based order penetration concepts.

Taking into account the different phases of the research, a few discussion points emerge in relation to the framework. The issue of 'level of analysis' is raised, where different levels of a complex project may sit within different categories within the framework. For example, at the top level a project may fall into a codes and standards category, whereas a subassembly or subcomponent may fit within the existing design category. This is to be expected, but researchers and practitioners utilizing the framework must be mindful of the hierarchical level at which they are analysing. Organizations may, therefore, find themselves managing a complex range of subcategories. A further issue that is raised is that the complexity in a project may not be inherent in the co-creation of bespoke engineering work, but rather from external constraints and issues found, for example, in the planning and financing stages. It may also be that a particular organization can develop maturity in particular type of engineering work, which makes it less 'novel' than would be the case for another company (i.e. they build up expertise and capability). At a strategic level, we do argue that is it possible for a company to articulate a position in relation to the subclasses and to align their capabilities and procurement approaches around that position. The ways in which this might be done are a fruitful line of future research.

While the framework presented has been shown to have credibility, as evidenced by the focus group and case studies, the research nevertheless has a number of limitations. Firstly, a warning must be added in terms of the generalizability of findings. The study is based on a limited number of cases and sectors and care should be taken in applying the framework developed in new contexts. While research participants indicate that the framework is of relevance, we have to be aware that this may be due to the nature of those particular industry environments in which the participants operate. Secondly, some of the case studies only included single interviewees. Hence, wider scale investigation in different sectors, and more extensive testing through survey based research, would be welcomed. Future research is needed to fully understand the way in which the project environment and context, in addition to the technical solution, shapes the positioning and choice of subclass as typified via Figure 5. The completeness and sufficiency of the proposed continuum should also be established through wider scale testing across different sectors. Although this paper develops some foundations, the full implications and alignment strategies for different subcategories are not yet established. Finally, an additional agenda for future research would be to understand how the framework relates to new product development processes in non-ETO organizations.

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9. APPENDIX 1

Stages	Protocol, Activities and Key Areas of Discussion
Stage 1 – Establish Scope and Purpose	• General introductions and explain purpose • Agree an area to focus the discussion on that is relevant to engineer-to-order and customer penetration
Stage 2 – Present Framework	• Present framework, either electronically or through physical handouts • Provide an opportunity for interviewees to register first impression and ask any initial questions.
Stage 3 – Discussion of Framework	• Are the engineering subclasses recognizable, understandable and complete? • How do current or previous projects relate to the framework? • What are the penetration points? How do you interact with customers?
Stage 4 – Discussion of Implications	• How could this framework be used? • What are the implications of shifting forward and backward through the subclasses? • Do different subclasses require different approaches?
Stage 5 – Site Tour	• Relate back to stage 3, and , if possible, directly observe relevant sites for the projects discussed. • Further clarify any details in relation to penetration points and the implications
Stage 6 – Email follow up	• Summarise key points and give opportunity for further comment and clarification. • Agree on subclass position.

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